

Electromagnetic Wave Propagation over Large Rough Surfaces at Low Grazing Angles using Periodic FMM

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Prediction of electromagnetic wave propagation over rough sea surfaces at low grazing angle is important in many areas of interest to the Navy, such as ship-to-ship communications and detection of low altitude targets over the sea. In order to reliably predict the radar coverage within an ocean environment, one must accurately account for the effects of the wind-driven ocean roughness on radar propagation. In general, the goal is to obtain knowledge of the mean value of the signal strength, the amplitude of the fluctuations about the mean, and the spectrum of the fluctuations.

In this last year of the project, extensive numerical data has been generated using the full-wave integral equation method described in the previous annual report. In this formulation, the rough surface is assumed to be periodic to avoid artificial edge effects. The period of the surface is chosen to be large enough so that there are many peaks and valleys of the height profile within one period so that the results obtained from periodic surfaces are a good predictor for the infinite-surface case. Our primary goal was to study the statistical properties of the scattering amplitude and develop a rough surface scattering model that is especially suitable for scattering from a very rough surface at low grazing angles. Questions such as *whether the coherent reflection coefficient is adequate to describe the scattering phenomena* and *whether the coherent component continues to dominate for large roughness and low grazing angles and at what point the diffuse component takes over* were answered as they have not been addressed in the literature definitively.

Some example plots are shown below for the ratio of coherent power scattered to either the incoherent power or the total power scattered by the rough surface. These power quantities are described in terms of the propagation factor, F , defined as

$$F = \frac{E_{\text{tot}}}{E_{\text{inc}}} = \frac{E_{\text{inc}} + E_{\text{sca}}}{E_{\text{inc}}} = 1 + \frac{E_{\text{sca}}}{E_{\text{inc}}},$$

which is the ratio of the total field to the incident field due to the direct path. The propagation factor is separated into coherent and incoherent components. The coherent component is the power of average field and is expressed as $P_c = \langle |F| \rangle^2$. The incoherent component is the mean of the variance of F and is expressed as $P_i = \langle |F - \langle F \rangle|^2 \rangle$. In these definitions, $\langle \cdot \rangle$ denotes ensemble average over many realizations.

Fig. 1 show the coherent/incoherent power for various wind-speeds $U = 1, \dots, 15$ m/s for the Pierson-Moskowitz sea spectrum at a frequency of 3 GHz and a grazing angle of $\psi = 1^\circ$. Data is shown for the

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14. ABSTRACT Prediction of electromagnetic wave propagation over rough sea surfaces at low grazing angle is important in many areas of interest to the Navy, such as ship-to-ship communications and detection of low altitude targets over the sea. In order to reliably predict the radar coverage within an ocean environment, one must accurately account for the effects of the wind-driven ocean roughness on radar propagation. In general, the goal is to obtain knowledge of the mean value of the signal strength, the amplitude of the fluctuations about the mean, and the spectrum of the fluctuations.					
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P_C / P_{tot} as a function of receiver height. As the grazing angle is decreased, the onset of coherence is clearly seen by the appearance of nearly flat curves. In this case coherence can be assumed for all angles below $\psi = 11^\circ$.

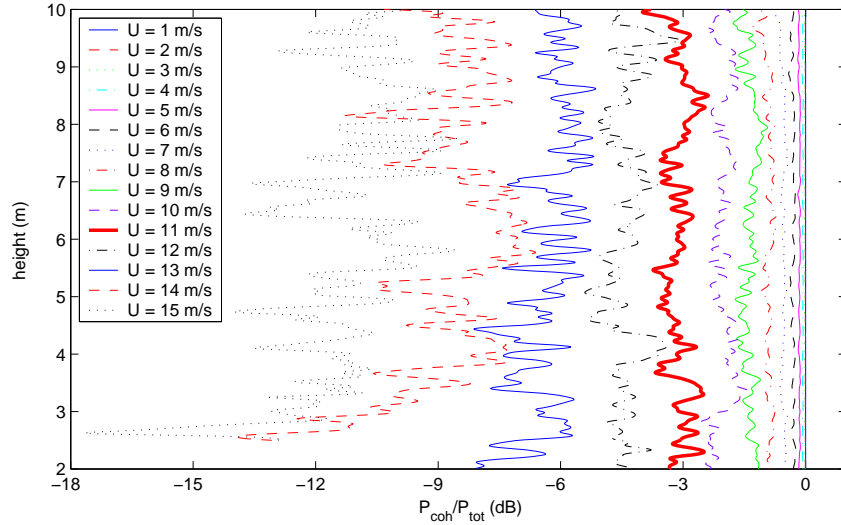


Figure 1: The ratio of the coherent power to the total power for the Pierson-Moskowitz spectrum for $f = 3$ GHz and $\psi = 1^\circ$.

Fig. 2 shows P_C / P_{tot} for various grazing angles $\psi = 1^\circ, \dots, 15^\circ$ for a wind speed of $U = 5$ m/s and a frequency of 3 GHz. Fig. 3 shows the data at a wind speed of $U = 10$ m/s. It is seen from these plots that coherence of the received signal can be assumed for $\psi \leq 4^\circ$ at $U = 5$ m/s and for $\psi \leq 1^\circ$ at $U = 10$ m/s.

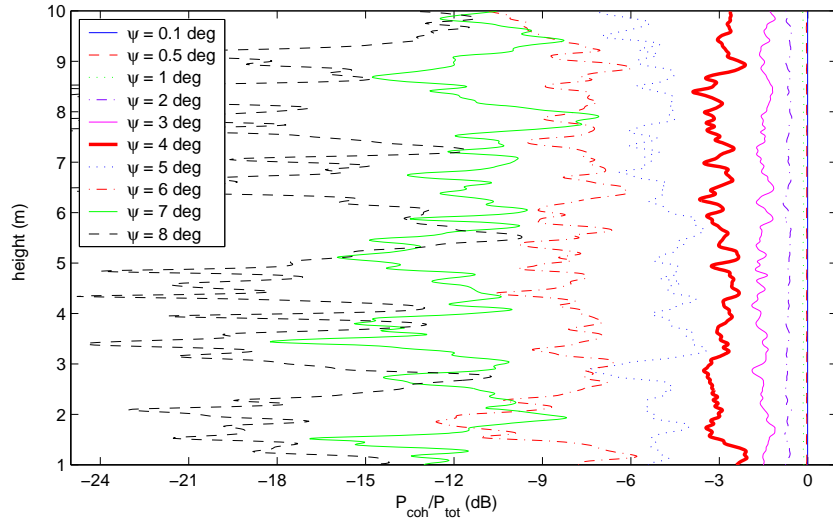


Figure 2. The ratio of the coherent power to the total power for the Pierson-Moskowitz spectrum for $f = 3$ GHz and $U = 5$ m/s.

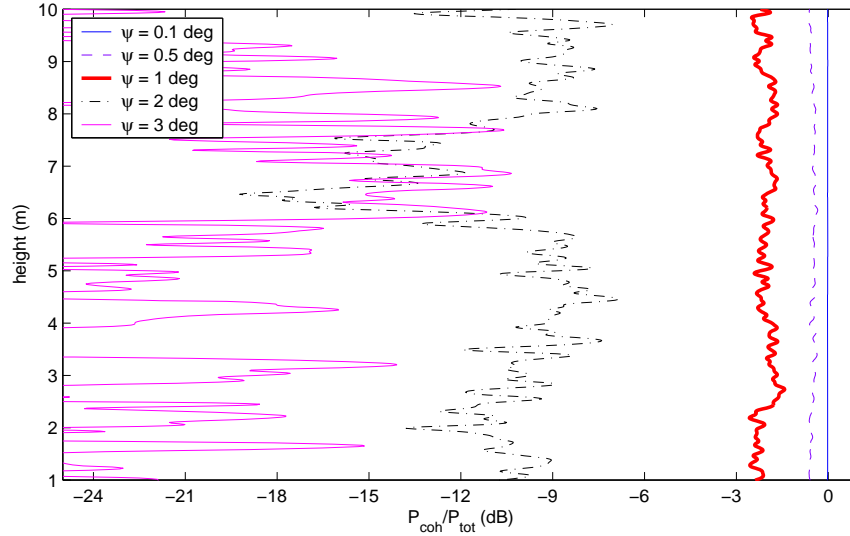


Figure 3. The ratio of the coherent power to the total power for the Pierson-Moskowitz spectrum for $f = 3$ GHz and $U = 10$ m/s.

The main conclusions that could be drawn from the extensive numerical results generated in [1] are:

(1) For electromagnetic wave propagation over rough surfaces, the well known Rayleigh parameter, $R_a = k_0 \sigma_h \sin \psi$ is in some sense a very good indicator of the surface roughness since it illustrates the important point that the roughness of any surface is not only an intrinsic property of that surface but also depends on the properties of the wave being scattered. Both the radio frequency and the angle of incidence determine how ‘rough’ any surface appears to be. Roughly speaking, specular reflection (i.e., the coherent power) dominates when $R_a \leq 0.5$. As R_a increases, the coherent power decreases and the incoherent component starts to take over. When $R_a \geq 2$, the coherent component almost vanishes and only the incoherent component exists. However, a single Rayleigh parameter is usually inadequate to describe the wave propagation phenomena as many physical quantities of interest, such as the coherent (field or power) reflection coefficient, depend on the Rayleigh parameter as well as the grazing angle. Further studies showed that the coherent power reflection coefficient is independent of the surface spectrum, whereas the coherent field reflection coefficient (usually complex) does depend on the surface spectrum. In all the cases considered, the Rayleigh roughness reduction factor (i.e., the Ament expression) overestimates the decay of the coherent power, whereas the Miller-Brown-Vegh roughness reduction factor underestimates the decay of the coherent power when the grazing angle is not very small.

(2) In the case when the specular reflection dominates, it is sometimes useful to replace a random rough surface by a flat immittance surface such that they both produce the same reflection coefficient for the specular wave. At low grazing angles, numerical results showed that almost all the power is scattered in the forward direction even when the surface roughness is large (i.e., when R_a is large), thus validating the parabolic approximation. The Fourier split-step techniques based on forward propagation approximation thus become extremely attractive for long range

propagation prediction because of their numerical efficiency and their ability of incorporating atmospheric variations as long as the mean field is concerned. In split-step parabolic equation solutions, it is usually a robust approach to use the complex refractivity as a domain termination.

(3) Studies on the statistical properties of the scattering amplitude showed that the mean scattering amplitude follows a delta-like function (vanishes everywhere but the specular direction) and it is uncorrelated at different scattering angles, resulting in a scattered field whose autocorrelation function depends only on the position difference. Unlike the scattering amplitude, the scattered field does follow some form of non-delta-like autocorrelations and it decorrelates more rapidly when the surface is rougher. Further studies on the incoherent component of the scattered field show that both the in-phase and the phase-quadrature components of the specular term follow Gaussian probability densities. For $0 < R_a \leq 1.5$ the two components usually have different variances and the correlation coefficient between them is usually significant. For Gaussian surface spectrum, the phase-quadrature component always has a larger variance than the in-phase component in this region. For the Pierson-Moskowitz spectrum, this is only true when the grazing angle is not very small. As R_a increases, the two variances become equal and meanwhile the correlation coefficient becomes reasonably small (for both the Gaussian spectrum and the Pierson-Moskowitz), suggesting that specular component can be described as Rayleigh distributed for large roughness. The incoherent component of the non-specular terms, on the other hand, always follows Rayleigh distributions. The incoherent component of the scattered field is also always Rayleigh distributed, i.e., the in-phase and the phase-quadrature components have the same variance and the correlation coefficient between them is small.

REFERENCES

[1] Z. Lai, *Electromagnetic Wave Propagation Over Large Rough Surfaces at Low Grazing Angles*, Ph.D. Dissertation, University of Massachusetts, September 2007.